

Electron Tubes in World War II*

JOHN E. GORHAM†, MEMBER, I.R.E.

Summary—Although the military uses of electronics have been well publicized in technical journals, the improvements in electron tubes that made possible these military innovations have not been fully reported. While this information is known in some detail by the technical people who were engaged in various phases of tube research and development, an over-all summary of the work done by industrial laboratories and Federal agencies has not been available to many engineers and students interested in this field. In this paper, the status of electron-tube development at the close of the war is indicated in broad outline; a more comprehensive picture depends upon more detailed reports from the various laboratories engaged in war activities.

This summary of wartime advances in electron tubes is based on the knowledge of the vacuum-tube field gained by the engineers of the thermionics branch of the Signal Corps Engineering Laboratories, Bradley Beach, New Jersey, in developing, standardizing, and giving type approval of all tubes procured for the army during the war.

No effort is made to give specific credit either to individuals or industrial organizations. By and large it is a story of common achievement of many people, with industry working hand in hand with the War and Navy Departments to meet the urgent requirements of an ever-expanding demand for new and improved military electronic equipment.

I. GENERAL RESEARCH AND MISCELLANEOUS RELATED TUBE PROBLEMS

Cathodes

AT THE start of World War II it was the practice to use oxide cathodes in low-power and receiving-type tubes, thoriated-tungsten filaments in medium-power tubes, and pure tungsten in high-power tubes. In general there were few power-pulse requirements. During the war, the use of thoriated filaments had been successfully extended to all types of power tubes, including the highest-power pulsed-oscillator tubes designed. In addition, during the last year of the war, oxide cathodes were used in power tubes capable of delivering 500 or 600 kilowatts peak power, and up to several megawatts peak power in magnetrons. The peak emission of thoriated filaments, for design purposes, has been increased from approximately 100 milliamperes per watt to approximately 200 milliamperes per watt. The peak emission from oxide cathodes has been increased to 30 amperes per square centimeter in production tubes, and as high as 80 amperes per square centimeter for several hundred hours in laboratory tubes. The highest peak emission reported is about 140 amperes per square centimeter. Oxide-cathode direct-current emission has been increased to approximately 0.5 ampere per square centimeter under optimum conditions.

* Decimal classification: R330. Original manuscript received by the Institute, March 27, 1946; revised manuscript received, July 31, 1946.

† Evans Signal Laboratory, Belmar, New Jersey.

There was little advance in the efficiency and stability of secondary-electron multipliers during the war. Electron multipliers may be considered to have a nominal multiplication factor of approximately 5 per stage for optimum acceleration voltages of the order of a few hundred volts per stage. After about 200 or 300 hours the performance of these multipliers is seriously reduced.

Except for low-power voltage-regulator and mercury-pool type tubes, relatively few tubes having cold cathodes were used in military equipment during World War II because of the lack of satisfactory life from such cathodes. In one type of pulse-modulator tubes, mercury is held in fine iron powder to permit use in aircraft. Mercury-pool ignitrons were used as pulsed modulator tubes to a limited extent.

It has been generally proved that at least 80 per cent of the total emission from the magnetron cathode is largely due to electrons emitted as a result of back-bombardment by electrons that do not reach the anode. As a result of such back-bombardment, considerable power is sent back to the cathode, with resultant heating and evaporation of the cathode coating and even the base metal. This has been overcome to some extent by appropriate reduction in power after the magnetron reaches stable operation. Some higher-frequency magnetron cathodes actually have radiators. More rugged types of coatings have been developed in which the oxides are pressed into a wire mesh which is sintered to a base cylinder, or in which approximately 50 per cent of the coating consists of 3- or 4-micron nickel powder to increase electron and heat conductivity and also to increase to some extent the binding force holding the barium.

Grids

An outstanding advancement during World War II has been the development of alloys and surfaces which overcome the problem of primary grid emission in thoriated-filament tubes, thereby eliminating the phenomenon of grid blocking, which normally leads to destruction of such tubes. These alloys include 4 per cent tungsten-platinum alloy wire, platinum-coated molybdenum-core grid wire, and "mossy"-surfaced tantalum or molybdenum wire.

It has been found that the presence of secondary emission tends to reduce the driving power of conventional grid tubes. The uniformity and stability of such secondary emission are very poor, however, and the current practice is generally to avoid making use of this factor in service tubes.

It has been discovered that there are certain temperatures at which the emission from grid wires is a minimum, and though it is not generally possible to maintain

the grids at this temperature, at least one tube type has been put into wide production with a fair degree of success using this principle. A second method used in receiving tubes (and, during the last years of the war, in power tubes) consists of the use of heat conduction to maintain grid temperature sufficiently low to minimize the effect of emission. This has been accomplished in some cases, such as in the 7C22, by the use of nickel cylinders with grid straps punched and rotated 90 degrees to reduce their effective cross section to electron flow but at the same time maintain their cross section for heat flow.

In various other power receiving tubes relatively large copper rods have been fastened at appropriate intervals to help remove heat. Another application makes use of very short grid wires to facilitate conduction to end rings. Still another method employed with moderate success in reducing grid emission involves the use of gold-plated molybdenum wire. It has been found that the gold will dissolve barium for at least 1000 hours in tubes such as the 715C. A solid solution is ultimately formed which apparently draws together and exposes the base metal through the resultant cracks.

Anodes

During World War II the problem of anode heat dissipation had not been a major one, except in planar-type lighthouse tubes. A principal problem in connection with anode design, and for that matter with general design of tubes, has been to reduce lead-reactance effects by providing extremely low-impedance paths at radio-frequency connections. The most important advance in anode design has been the development of various different but essentially similar re-entrant anode designs. These employ large-diameter glass-to-metal seals in both copper and kovar, and result in attendant reduction of lead-reactance effects up to at least 700 megacycles.

Zirconium or zirconium compounds have been sprayed on anodes to make them more nearly perfect black-body radiators, and simultaneously serve as getters. The principal requirement in planar-tube anode design at present is to improve heat dissipation and frequency drift due to warm-up.

Gas Reservoirs

Titanium-hydride reservoirs have been developed which are capable of maintaining the pressure at constant value and appreciably extending the life of hydrogen thyratrons under extreme operating conditions.

II. MAGNETRON TUBES

The development of the magnetron as an efficient microwave generator took place almost entirely during World War II. During the war, the magnetron advanced from the status of the elementary split-anode variety to

the highly perfected and complex multiresonant-cavity type. Operating efficiencies were raised from about 10 to over 50 per cent. Tubes were developed and produced in large numbers for wavelengths as short as approximately 1 centimeter. Representative types of magnetrons are shown in Fig. 1.

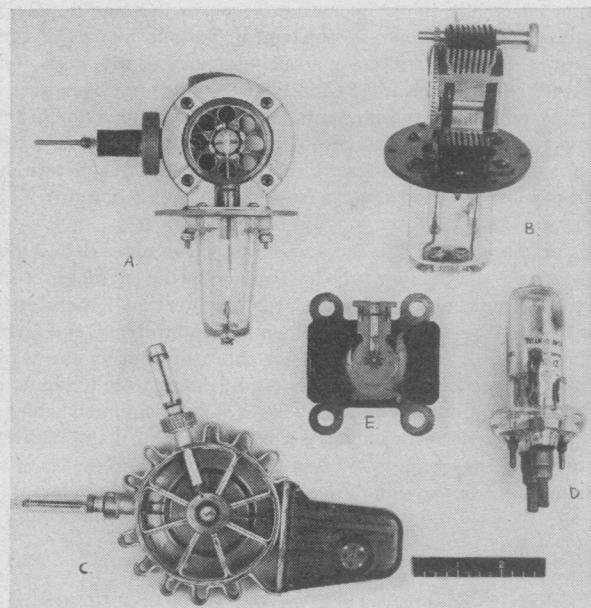


Fig. 1—Representative types of magnetrons: (a) 2J31 hole-and-slot pulse type. (b) 2J54 tunable pulse type. (c) 2J64 vane type for pulse communication. (d) 5J31 split-anode continuous-wave type. (e) 3J21 rising-sun pulse type.

During the course of the war, extensive studies were made of mode separation and the manner and efficiency of operation. Methods of eliminating undesirable modes (arising from multiple degeneracy due to the multiresonator anode blocks) were developed, such as strapping and the use of "rising-sun" alternately long and short cavity construction. The usual technique of strapping consists of electrically connecting alternate cavity vanes near the cathode ends by means of metal straps or wires within the tube. This strapping depends on end effects at the top and bottom of the vanes. The rising-sun anode construction consists of making alternate cavities tuned respectively to frequencies above and below the operating frequency of the magnetron, and was originated to avoid straps in super-high-frequency tubes. Lately, the fact that the rising-sun structure does not depend on end effects has been used in designing higher-power, longer-anode magnetrons.

Several mechanical tuning methods were developed. These include internal tuning by means of moving plungers in the resonant cavities ("crown of thorns"), changing the capacitance of the straps to ground and each other, the addition of an external tunable resonator coupled to an internal resonator or strap, and simultaneous application of strap and plunger tuning.

"Packaging" was also introduced, whereby the

magnetron was produced as a complete unit containing or having attached permanent magnets as an integral part of the magnetron instead of depending on the furnishing of proper magnetic fields as part of the operating equipment.

At present, several 25-centimeter pulsed magnetrons of fixed frequency are available with peak powers as high as 1 megawatt. Development has just been completed on a tunable type capable of 600 kilowatts peak power output and 8 per cent tuning range.

At wavelengths of about 10 centimeters, tubes have been produced in quantity with peak powers ranging up to approximately 2 megawatts. Tunable tubes have been made which have approximately 7 per cent tuning range and 1 megawatt peak power output.

The maximum peak power attainable at about 3 centimeters is approximately 1 megawatt from a fixed-frequency magnetron. A variable-frequency magnetron is also available at this frequency capable of 50 kilowatts peak power and 12 per cent tuning range. At about 1 centimeter only two fixed-frequency pulse magnetron types have been produced in quantity. The tubes are capable of peak powers of the order of 50 kilowatts. In general, the life expectancy of pulsed magnetrons is in the neighborhood of 500 hours, except at extremely short wavelengths where life expectancy is about 250 hours.

Continuous-wave magnetrons using split anodes in the high- and ultra-high-frequency bands, and cavities in the higher frequency bands, have been developed primarily as sources of jamming power of from over 1 kilowatt down to about 50 watts. Due to serious back-bombardment of the cathodes, tube life is usually less than 100 hours, although efficiencies are about 40 per cent. Interdigitated magnetrons, having as anodes two cylindrical sets of interlocking teeth, have been made to give about 15 watts output at 7 centimeters.

During the last part of the war, magnetron modula-

tion was investigated to permit communication at all frequencies. One electronic frequency-modulation method consists of varying the current of an electron beam through one of the magnetron cavities. This method has been used at 4000 megacycles to get 4 megacycles total swing at about 25 watts continuous-wave power output. Preliminary tests show that external magnetrons may be used to modulate the magnetron generator tube by virtue of change of electronic reactance, but at present modulation linearity is not as good as that obtained by the former method. Amplitude modulation is not satisfactory at this date, but there are indications that considerable success may be achieved in the near future. Pulse-time modulation is feasible at any frequency and involves transmission at constant power level.

III. TRANSMIT-RECEIVE TUBES

The transmit-receive (TR) tube (Fig. 2) is a switching tube, usually gas-filled, which is generally used in radio-frequency systems (radar, for example) where a transmitter and receiver make use of a common antenna. Its function is to protect the receiver input-circuit elements

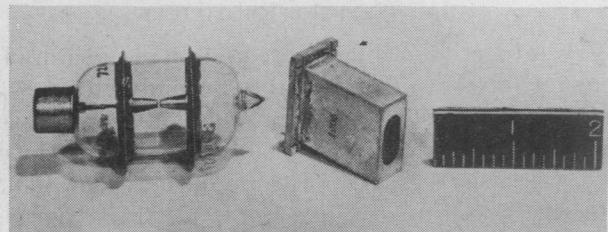


Fig. 2—Transmit-receive tubes: types 721A, 1B37.

during the pulsing of the transmitter and allow the radio-frequency power received by the antenna between pulses to reach the receiver. Antitransmit-receive (ATR) tubes are used in conjunction with TR tubes to reduce the dissipation of receiver signals in the transmitter.

TABLE I
TR-TUBE PERFORMANCE CHARACTERISTICS

| Type | Application | Wavelength | Power level | Insertion loss | Recovery time | Bandwidth |
|---------|----------------------------------|-------------------|---------------|-------------------|-----------------|-------------|
| 1B23 | TR | 20-50 centimeters | 50 kilowatts | 1 decibel | — | high Q |
| 702A, B | TR | 20-50 centimeters | 50 kilowatts | — | — | — |
| 721B | TR external cavity | 10 centimeters | 250 kilowatts | 1.0-1.5 decibels | <7 microseconds | high Q |
| 1B27 | TR external cavity | 10 centimeters | 250 kilowatts | 1.0-1.5 decibels | <5 microseconds | high Q |
| 1B58 | TR fixed-tuned | 8-11 centimeters | 200 kilowatts | 1.0-1.5 decibels | 15 microseconds | 10 per cent |
| 1B55 | TR fixed-tuned | 8-11 centimeters | 200 kilowatts | 1.0-1.5 decibels | 15 microseconds | 10 per cent |
| PS3S | TR fixed-tuned | 8-11 centimeters | 200 kilowatts | 1.0-1.5 decibels | 15 microseconds | 10 per cent |
| 1B44 | ATR fixed-tuned | 8-11 centimeters | 1 milliwatt | 1 decibel | — | 5 per cent |
| 1B52 | ATR fixed-tuned | 8-11 centimeters | 1 milliwatt | 1 decibel | — | 5 per cent |
| 1B53 | ATR fixed-tuned | 8-11 centimeters | 1 milliwatt | 1 decibel | — | 5 per cent |
| 1B56 | ATR fixed-tuned | 8-11 centimeters | 1 milliwatt | 1 decibel | — | 5 per cent |
| 1B57 | ATR fixed-tuned | 8-11 centimeters | 1 milliwatt | 1 decibel | — | 5 per cent |
| 1B38 | Pre-TR for use with low-power TR | 10.7 centimeters | 1 milliwatt | 0.10 decibel | 20 microseconds | — |
| 1B54 | Pre-TR for use with low-power TR | 8.4 centimeters | 1 milliwatt | 0.10 decibel | 20 microseconds | — |
| 1B24 | TR tunable self-contained cavity | 3 centimeters | 60 kilowatts | 1.0-1.5 decibels | <3 microseconds | high Q |
| 724B | TR external cavity | 3 centimeters | 60 kilowatts | 1.0-1.5 decibel | <6 microseconds | high Q |
| 1B63 | TR broad-band fixed-tuned | 3 centimeters | 300 kilowatts | <0.8 decibel | <5 microseconds | 12 per cent |
| 1B35 | ATR fixed-tuned cavity | 3 centimeters | 60 kilowatts | 0.8 decibel | — | 6 per cent |
| 1B37 | ATR fixed-tuned cavity | 3 centimeters | 60 kilowatts | 0.8 decibel | — | 6 per cent |
| 1B26 | TR self-contained cavity | 1 centimeter | 40 kilowatts | 0.85-1.5 decibels | <4 microseconds | high Q |
| 1B36 | ATR fixed-tuned | 1 centimeter | 40 kilowatts | 0.8 decibel | — | >2 per cent |

Pre-TR tubes are used for added receiver protection during transmitter pulses. These last two tube types have general requirements similar to that of TR tubes (see Table I). TR, ATR, and pre-TR tubes should have low leakage power to the receiver during the transmitter pulse, rapid recovery time immediately following the pulse to enable the maximum received energy to reach the receiver for short range echoes, and satisfactory life. Most tubes were filled either with argon or mixtures of hydrogen and water vapor at pressures in the range of 10 to 25 millimeters.

In general, the recovery time of good tubes at power levels of 30 kilowatts peak is in the order of 4 to 7 microseconds. At higher powers, recovery-time figures are progressively larger. For instance, at line powers of 100 kilowatts the recovery time is approximately 50 per cent greater than at 30 kilowatts. As might be expected, leakage power is also a function of line power. At 30 and 100 kilowatts the leakage powers are of the order of 20 and 75 milliwatts peak, respectively. The insertion loss is approximately one decibel. Recently multicavity fixed-tuned tubes have been made with a frequency coverage of about 12 per cent.

IV. CRYSTAL RECTIFIERS

Crystal rectifiers (Fig. 3) are used in receiver applications for mixers, video detectors, second detectors, and direct-current restorers. In construction they consist of a semi-conductor, either silicon or germanium, in contact with a cat's whisker of metal, usually tungsten. At present, crystal mixers give the lowest noise figures in receivers above about 1000 megacycles.

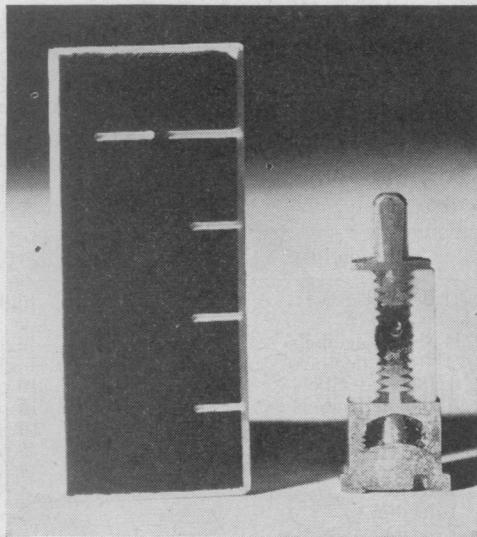


Fig. 3—Crystal detector: 1N21.

In general, microwave crystal converters have conversion losses of the order of about 6.5 to 8.5 decibels, being best at 3000 megacycles and worst at about 30,000 megacycles. They are capable of withstanding pulses ranging from 5 ergs at 3000 megacycles to 0.1 erg at 30,000 megacycles. On the basis of their use with an

intermediate-frequency amplifier of 5 decibels noise figure, receiver noise figures are attainable which vary from about 12.7 decibels at 3000 megacycles to 15.2 decibels at 30,000 megacycles.

Germanium crystals, used as second detectors, at present are capable of withstanding 50 or more volts in the back direction, compared with about 5 volts for silicon crystals. In general, they have rectification efficiencies in the same order of magnitude as receiving-type diode tubes. For direct-current restorer applications, germanium crystals have resistances, measured at 1 volt, greater than 0.1 megohm in the back direction and approximately 200 ohms in the forward direction. Germanium crystals are being used at present as second detectors and direct-current restorers for experimental circuit work. Their properties, especially as compared to diodes, are being studied.

V. KLYSTRONS

Development and application of klystrons during World War II has mainly centered about reflex tubes for local-oscillator use, requiring about 20 milliwatts of power output, and signal-generator use, requiring about one watt. Although the theoretical maximum efficiencies are 30 per cent for the reflex klystron and 58 per cent for the two-cavity type, the actual efficiencies thus far attained are only a few per cent for reflex tubes and 5 to 6 per cent for two-cavity types. The best tube in this respect, to date, is the 2K54 for which efficiencies of 10 per cent are obtained under pulsed operating conditions.

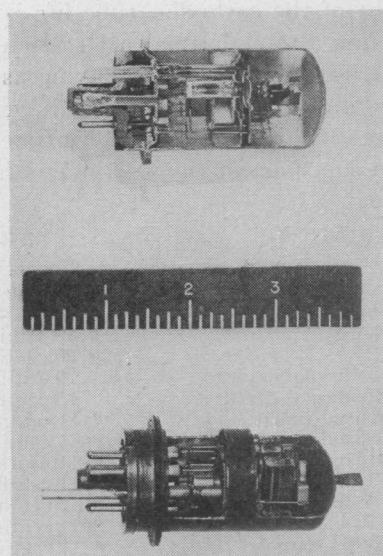


Fig. 4—Thermally tuned reflex klystron, 9000 megacycles: type 2K45.

Tuning of klystrons is generally accomplished by either changing the resonant frequency of the cavity or, in the case of reflex klystrons, by varying the potential of the repeller. Repeller-voltage changes are capable of producing only relatively small frequency changes of the

order of 1 per cent. The degree of frequency change attainable by means of cavity variation depends largely on the cavity construction. Klystrons designed to operate with external cavities may have frequency tuning ranges in the order of 2 to 1. Klystrons constructed with cavities which are an integral part of the tube usually are tuned by the motion of a metal diaphragm, which permits variation in the spacing of the resonator grids. This produces changes in grid-to-grid capacitance and consequent shift in the resonant frequency.

Tuning has also been accomplished in some tube types by electronic control of an auxiliary electron source within the same envelope, which heats a thermally sensitive mechanical element attached to the cavity diaphragm. The thermal time constant of such devices varies between 2 and 10 seconds, depending on the type of tube. Tubes with thermal tuning are available in the regions of 10,000 and 25,000 megacycles (Fig. 4).

The power output of reflex klystrons below 3000 megacycles is of the order of 1 watt. Between 3000 and 10,000 megacycles, $\frac{1}{4}$ watt may be attained. Above 10,000 megacycles, available types exist only in the region of about 25,000 megacycles and are capable of approximately 20 milliwatts output. Two-cavity klystrons have been produced in the 2300- to 4000-megacycle region, capable of delivering between 20 and 40 watts of power.

VI. PLANAR TUBES

Planar-type tubes (Fig. 5) are suitable for high-frequency operation because of (a) reduction in lead inductances by use of disk seals, (b) reduction in interelectrode capacitances by means of small electrode areas

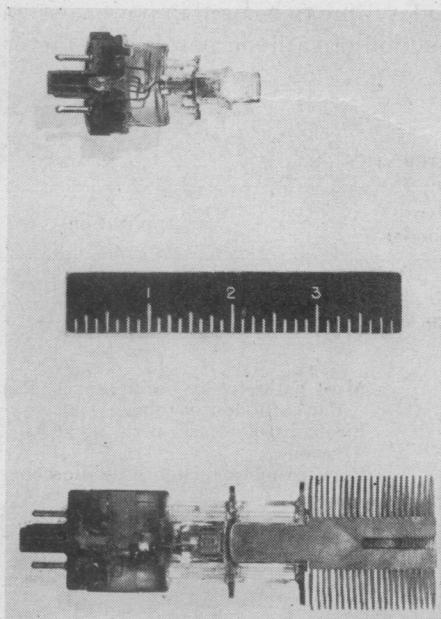


Fig. 5—Cutaway planar tubes: types 2C43, 3C22.

and parallel-plane structure, and (c) essentially complete enclosure of the radio-frequency fields permitted by a tube construction suitable for operation in an inclosed cavity. A number of types, all developed during World War II, are now available. These include the 2C40, a low-power triode with 50 milliwatts output at 3370 megacycles; 2C43, a pulse triode with 750 watts peak

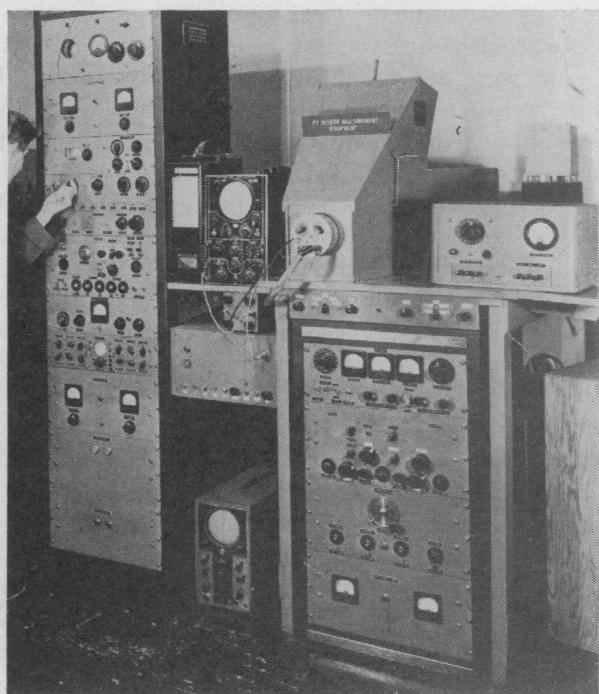


Fig. 6—Cathode-ray-tube screen test.

output at 3370 megacycles; 3C22, a continuous-wave triode with 25 watts output at 1400 megacycles; 2C38, continuous-wave triode with 10 watts output at 2500 megacycles; and the 2C36 and SB846A, British-type disk-seal triodes for low-power use up to about 4000 megacycles.

Present types of planar tubes are constructed with oxide-coated cathodes; tungsten or nickel grids; and steel, molybdenum, or kovar plates. The glass seals are made to silver-plated steel or kovar. In the case of silver-plated steel, special glass having a thermal-expansion coefficient equal to steel is used. Interelectrode spacings on the 2C40 type are as low as 0.003 inch and 0.010 inch for grid-to-cathode and grid-to-plate, respectively. These small spacings, in view of the fact that such tubes are intended for use in accurately machined cavities, require unusually small mechanical tolerances in manufacture.

VII. INDICATOR AND PICKUP TUBES

Cathode-ray indicator tubes are used wherever a visible indication of rapidly changing electrical phenomena is required. Because of the almost infinitesimal inertia of the electron beam, these tubes are capable of responses far more rapid than any mechanical indicators.

The transforming of visible or invisible radiation images into electrical signals is accomplished in electronic pickup tubes. Such tubes are designed to have high sensitivity to radiation. By means of very rapid electronic scanning of a photosensitive mosaic, high-resolution electrical transmission of rapidly moving images is accomplished.

During the war, the following improvements were made in electron guns:

(a) In electrostatic-focus types, zero first-anode-current guns were developed in which the first anode did not intercept any beam current, with the result that power-supply requirements were reduced and better focusing control was obtained.

(b) In magnetic-focus types an additional cylinder was added to the high-voltage anode, which aided in alignment of the gun and improved the focus.

(c) Limiting apertures were added in magnetic-focus types to reduce the spot size and improve the focus.

With regard to screens, several new types were developed:

(a) Double-layer screens which have the property of emitting increased intensities of persistent light after successive excitations of the screen. The color of its fluorescent light is different from that of its phosphorescent light.

(b) Dark-trace screens showing a darkening of the normally white screen material, usually potassium chloride, at the point of excitation by the electron beam, were used in projection systems.

(c) Exponential screens having light output which decays at such rate that its instantaneous intensity is proportional to exponential t/t_0 , where t_0 is a constant of the screen and t is the time.

Commutator tubes of several varieties were developed during the war for multichannel communication over a single transmission frequency.

Improved tubes suitable for projection purposes were also developed during the war with high light output

(6 candle power per watt) and good contrast. Cathode-ray tubes with two or more guns in the same envelope were developed for special applications, eliminating complex switching circuits. Pickup tubes were developed with sensitivities in the infrared. Tubes were also developed capable of converting infrared images directly to visible images by focusing the electron pattern from a photosensitive surface on a fluorescent screen at the opposite end of a cylindrical tube.

At present, cathode-ray tubes with faces from 1 to 12 inches in diameter are available in quantity. These tubes are in some instances focused and deflected by electrostatic methods and in others by magnetic methods.

The various screen types and general information concerning their properties are listed in Table II.

Levels of fluorescent light output vary according to screen types, being about 15 foot-lamberts for tubes of the highest output (nonprojection tubes with P1 screens). Improvements in focusing and line widths were limited and were less than a factor of 2 to 1. Present line widths of from 0.3 millimeter to 1 millimeter are a function of tube size and gun construction (Fig. 6).

Pickup tubes of the orthicon type have been produced with sensitivity in the infrared and in the blue part of the spectrum. Orthicon tubes have been made with a resolution of 1500 lines per frame at the center for high resolution reconnaissance work. For portable systems, tubes have been constructed operating with only a few hundred volts having a sensitivity of 0.03 microamperes per foot-candle.

VIII. POWER AND GAS TUBES

At the start of World War II radar transmitters were operated at or below about 200 megacycles and used tubes which had thoriated filaments. During the war oxide cathodes came to be used in power-oscillator tubes with a reduction of cathode power by a factor of about five.

TABLE II
CATHODE-RAY-TUBE SCREEN CHARACTERISTICS

| Screen type | Composition | Color | Persistence | Decay time to 1 per cent (seconds) | Applications |
|-------------|--|----------------------|-------------|------------------------------------|---|
| P5 | $\text{CaWO}_4:(\text{W})$ | Blue | short | 10^{-5} | Photography of rapid transients (to 60 kilocycles). |
| P11 | $\alpha^*-\text{ZnS:Ag}$ | Blue | short | 0.005 | Photography of transients (to 9 kilocycles). |
| P4 | $\alpha^*-\text{ZnS:Ag}$ + $\text{Zn}_8\text{BeSi}_3\text{O}_{19}:\text{Mn}$ | White | short | $0.005 + 0.06$ (B) (Y) | Television. |
| P1 | $\text{Zn}_2\text{SiO}_4:\text{Mn}$ (α) | Green | short | 0.05 | Most cathode-ray oscilloscopes. Rapid-scan radar cathode-ray tube. |
| P12 | $\text{Zn}(\text{Mg})\text{F}_2:\text{Mn}$ | Orange | long | 0.4 | Fire-control radars operating at 4 to 16 scans per second. |
| P2 | ZnS:Cu(Ag) (β^*) | Green | long | 0.3 | Prewar long-persistence oscilloscopes. |
| P14 | $\beta^*-\text{ZnS:Ag}$ on $\text{ZnS(75)}:\text{CdS:Cu}$ | White ↓ Orange | long | 1 | Eagle and H2K radars operating at about 1 scan per second. |
| P7, (P8) | $\beta^*-\text{ZnS:Ag}$ on $\text{ZnS(86)}:\text{CdS:Cu}$ | White ↓ Yellow | long | 3 | Most radars operating slower than 1 scan per second. |
| P10 | KCl | Magenta on White | long | 5 | Radars operating in high ambient light and slower than 0.2 scan per second. |

Several types of $\frac{1}{4}$ - to $\frac{1}{2}$ -megawatt triode tubes have been developed with the tuned circuits inside the vacuum envelope. By the close of the war, triode oscillator tubes had been developed which gave approximately 0.6 megawatt up to about 700 megacycles. Power-amplifier tubes are available that can handle 100 or 200 watts continuous-wave output up to 700 megacycles with a power gain of about 5 decibels.

Hydrogen thyratrons were originated and put into production during the war to eliminate temperature dependence of mercury tubes. These thyratrons handle powers of from a fraction of a watt to 2 megawatts pulse power. Series and/or parallel operation of thyratrons

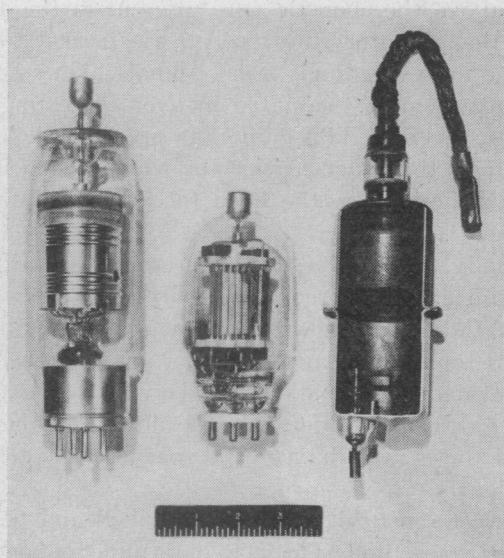


Fig. 7—Pulse modulator tubes: 5C22 hydrogen thyratron; 715C high-vacuum type; 1R21 mercury-pool ignitron.

has been accomplished to allow up to four times the power of a single thyratron. Ignitrons have been used up to 2 megawatts at 20 microseconds pulse width. High-vacuum modulator tubes have been developed to handle a few hundred kilowatts peak power at duty ratios of about 0.0006. Tubes of each of these types are shown in Fig. 7.

The resonatron, employed during the war in radar countermeasures to jam German radar, is the most powerful ultra-high-frequency oscillator and amplifier now in existence. It supplies over 50 kilowatts in continuous-wave operation at frequencies ranging from 350 to 650 megacycles, with a plate efficiency of the order of 60 to 70 per cent. Features of this tetrode include beam-forming grids, electron bunching, and self-contained resonant cavities which permit phase-shift compensation for transit-time effects without lowering efficiency.

IX. RECEIVING TUBES

There are so many types of receiving tubes that it is impossible to begin to describe them here. Consequently only a few practices of a general nature that came into considerably wider employment during the war will be

mentioned in this section. The use of standard tubes at low plate and screen voltages was accomplished to allow operation directly from a 24-volt storage battery in place of a high-voltage power supply. Subsequently, tubes with 26.5-volt filaments and a design optimized for 28-volt plate and screen operation were developed. Tubes were "ruggedized" to withstand vibration and shock up to 500 times the acceleration of gravity. Subminiature tubes (T-3 bulbs of $\frac{3}{8}$ -inch diameter) were in existence before the war for hearing-aid use. During the war, subminiature types for VT fuzes were developed which could withstand being shot from guns. Size and weight limitations of new radar and allied equipment, along with the need for high peak power output, created the need for receiving-type tubes capable of operating in a pulsed condition at potentials and currents far above their rated values. Fig. 8 shows six different types of receiving tubes.

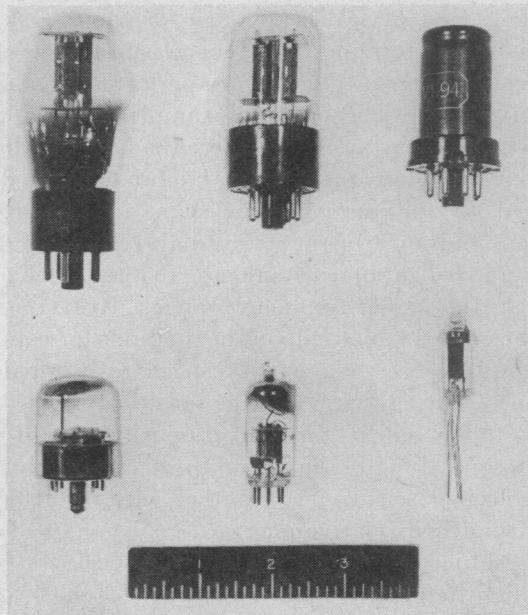


Fig. 8—Receiving tubes having transconductances of 3000 to 5000: G, GT, metal, lockin, miniature, and subminiature tube types 6J5G, 6J5GT, 6J5, 7F8, 6J6, 6K4.

There is now an overabundance of receiving-tube types—one or two thousand, or perhaps more. It is not unusual to find half a dozen or more tubes, substantially equivalent, differing by having several filament voltages, two or three types of bases and bulbs, and different arrangements of pin connections. Almost every metal-tube type is duplicated in a glass version with the same base, and most are also duplicated in lock-in construction under different type designations. Now most of these types are becoming available in miniature bulbs.

X. ACKNOWLEDGMENT

It is a pleasure to acknowledge the aid of my associates in the preparation of this paper: M. E. Crost, K. Garoff, D. R. Gibbons, L. L. Kaplan, B. Kazan, H. L. Ownes, D. E. Ricker, and C. S. Robinson, Jr.